Classification of vibration diagnostic systems Brush-collector assembly

Olga Filina[1], Azat Khusnutdinov[1],Khalil Vakhitov[1], Aida Abdyllina[1]
Kazan State Power Engineering University
Kazan, Russian Federation
[1]olga_yuminova83@mail.ru

Olga Salnikova
Kazan State University of Architecture and Engineering
Kazan, Russian Federation
olgamutter2001@gmail.com

***Abstract*—This article discusses the classification of vibration diagnostics and control of exposure to objects in order to change their behavior in the desired direction. The set of elementary checks, the sequence of their execution is based on the residual service life of the electric brush of the DC electric motor, containing a list of monitored reliability indicators included in the mathematical model. The described model, using vibration diagnostics, improves the accuracy of predicting and detecting DC motor failures. The conclusion of the general formula for calculating the residual life of the electric brush is given and the method of increasing the prediction using the methods of vibration diagnostics of studying the life of the electric brush is considered.**

***Keywords — brush contact, approximation, electric brush,* vibration, brush holder.**

I. Introduction

At present, there is a significant number of the high power DC electric motors (DCEM) are counted for a certain service life. As it expires, the reliability of DC motors decreases. DC electric motors' remaining life's extension provided by developing their construction and predicting technical condition is meant to be economically effective, because it allows to significantly decrease and minimizenumber of random failures of DCEM brush-collector assembly (BCA), decreasing emergency of EM and reducing economic costs of technical service and repair [1].

The main assembly of DCEM is being BCA, affecting the service life. Its failure leads to workability loss of whole electric motor. Due to lack of modern methods of BCA technical condition control and timely taken actions for workability restore nearly 50-60% of DCEM fail before the overhaul deadline [2].

The brush is a non-recoverable part of the design of the safety unit. The value of residual life of the brush is indicated by such an indicator as its height. This value is the main indicator in the developed method of service life prediction and is included in the mathematical model [3].

The main operational influence on the occurrence of brush failure, and as a consequence, on its resource and reliability, is the influence of brush wear rate [4]. Brush wear rate can be taken as an indicator of stability and quality of DCEM operation.

As researches of the authors of this work have shown, during long-term operation of a brush brush inevitably damages brushes or breaks of serviceability of its elements, even in the absence of manufacturing defects and observance of the rules of operation. In this case, there is a dynamic development of micro-defects on the brush surface, because it is constantly under pressure and is a loaded element, and deposits on the collector plates, prevent the flow of technical process regulated by the manufacturer (current consumption) [5].

Thus, the research aimed at identifying the causes of failure of DCEM's switchgear and development of measures to improve the residual life, is relevant and important. For this purpose, it is necessary to develop and improve methods of reliable diagnostics and evaluation of technical condition of elements and units of DCEM.

In monitoring of brush-collector assembly of DCEM during operation is given. The spark indication device was suggested. It revealed the dependence of the voltage value on the sparking. This monitoring considers only the sparking, and the other parameters are not affected. Some authors [6] note that a possible method of reliability assessment is its modeling for unique, single objects.

At present in different fields of DCEM application there are methods of reliability indices forecasting, differing by the set of solved tasks and peculiarities of applied mathematical apparatus [7]. Thus, it can be concluded that the production and long-term trouble-free operation of electric machines largely depends on the quality of assembly units and parts, used in DCEMs and their reliability in operation.

II. Advantages of the work

When calculating the traction power supply system, there can be two types of tasks:

- It is required to determine all design values with respect to a certain train schedule (e.g., subway trains);

- It is required to determine all design values under conditions when a certain train schedule cannot be specified (this applies to train traffic on mainline sections of railroads).

The most widely used in educational, design and operational practice methods of calculation of traction power supply systems can be divided into three groups:

1) methods of calculation according to a given train schedule;

2) methods of calculation according to average dimensions of train traffic;

978-1-6654-1434-0/22/$31.00 ©2023 IEEE

3) methods of calculation taking into account irregularity of train traffic.

In the theory of the organizational systems management, all the systems under consideration can be classified (fig. 1):

- by the conditionality of the structure and behavior of the system degree;

- by the degree of the structure and behavior of the system complexity;

- by the behavior of the system purpose.

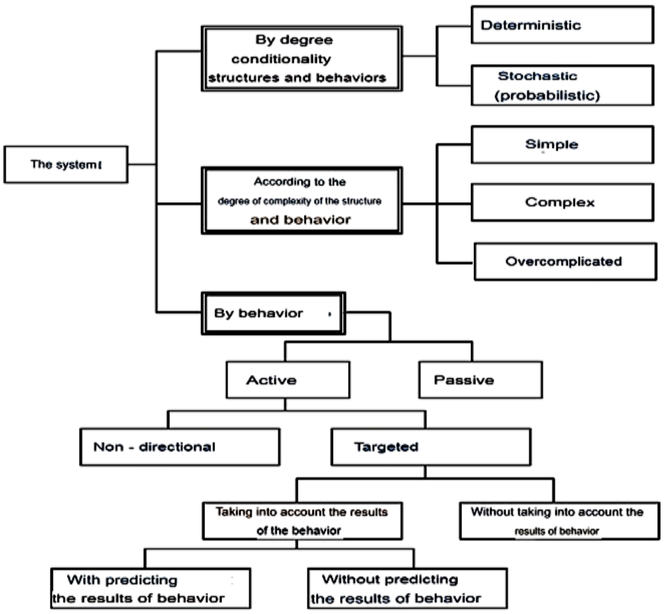

Fig.1 - Classification of systems

Deterministic and stochastic (probabilistic) systems are distinguished according to the degree of conditioning of the structure and behavior of the system.

Deterministic systems have a definite structure and behavior. Such systems clearly respond to external influences. Writing a full description of these systems is possible even in case of a large number of elements and connections in the system [8].

If there is known, for example, the state of the system and the program of its transition, then it alwayspossibleto accurately describe the state to which the system will go under the influence of various influences.

In probabilistic systems, elements interact with each other and with the external environment at random. Such a system always remains uncertain to some extent, and the description of its future behavior never goes beyond the probabilistic categories by which it is described. A full description of probabilistic systems is possible only within this framework at the level of quantitative characteristics and laws of probability distribution of systems states [9].

In terms of complexity, structures and behaviors are distinguished between simple, complex, and very complex (super complex) systems.

Systems with few elements and links between them are considered simple; the elements of such systems are also simple. The simplicity of the elements means that with sufficient accuracy of the property and the regularity of changes in the condition of the elements can be described by known mathematical relationships.

Complex systems have many elements and connections between them. They have an extensive structure and their elements perform complex functions and are themselves complex systems [10].

However, these systems can be reduced to a simple system by the introduction of the simplicity hypothesis, which allows a mathematical description of such systems with sufficient accuracy.

Very complex (super complex) systems have an exceptionally large number and variety of elements and connections between them. No amount of detailed knowledge of the structure and behavior of the elements of such systems makes it possible to determine the complete behavior of the systems, No precise knowledge of the behavior of a super complex system at any finite interval in the present makes it possible to accurately predict its behavior at any finite interval in the future [11].

In terms of targeting, systems are divided into targeted and non-targeted (casual).

Targeted (goal-oriented) are systems whose behavior is aimed at achieving a goal.

Systems whose behavior is not tied to the presence of a target are referred to as non-targeted.

The goal is the desired result of the activity, which can be achieved within a certain interval of time.

Such a notion of purpose is inherent in highly organized systems, which include conscious living beings.

For technical systems, the target is the state to which the system aspires. The organization and behavior of the system were aimed at achieving that condition.

The organizational systems for the classification are considered stochastic, complex and highly complex systems with active, targeted behaviors, taking into account and predicting the results of this behavior. Such complex, targeted behaviors are possible only if the system has the ability to change its behavior in the right direction. The property that characterizes this capability of the system is called manageability, the impact on the system to change its behavior in the right direction - management, and the systems that implement the management process - management systems [12].

After performing the algorithm for determining the technical condition of the brushes, the decision of brushes replacement need is made and the final decision on the amount of necessary repair is formed.

There was carried out experimental studies of motor brushes wear in transport enterprises of Kazan.

According to the results of the experiment and data collection about operation and wear rate of electric brushes, an array of information about experimental and statistical data about the wear rate of electric brushes was created. In the course of experiment were investigated electric brushes EG61AK brand on electric motors with a total number of 85 units of rolling stock [13] MUE"Metroelectrotrans" (Tram depot and Trolleybus depot № 2) of Kazan. Kazan and

Gorkovskaya railway on the basis of Yudino-Kazansky service locomotive depot, LLC LokoTech-Service branch Zapadniy.

A management system is a system that makes appropriate (purposeful) behavior possible by developing and influencing the system elements.

A managed system is a management system subsystem consisting of objects that are impacted to ensure that the management system behaves appropriately.

The control system is a management system subsystem that develops and influences the managed subsystem to ensure that the management system behaves appropriately.

The structural diagram of the control system, presented in the form of interactive control and managed systems, is given in Fig. 2.

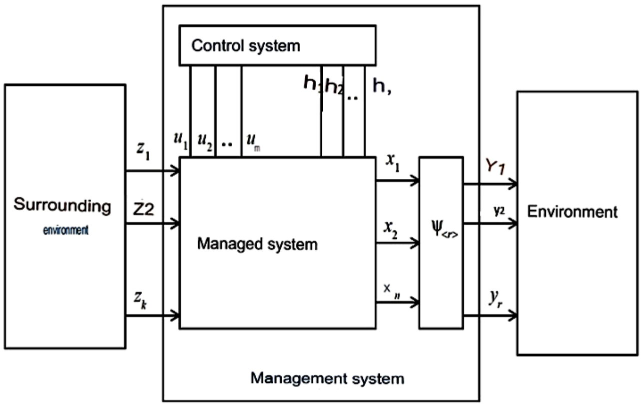

Fig. 2 - Flow chart

The diagram assumes the following designations:

$Z_{<k>}(t)=<z_1(t),\ z_2(t),\ ...,\ z_k(t)>$ - perturbing variables characterizing the environmental effects on the control system at time t;

$U_{<m>}(t)=<u_1(t),\ u_2(t),\ ...,\ u_m(t)>$ - controlling variables The ha-specific targeted effects of the control system on the managed system at time t;

$X_{<n>}(t)=<x_1(t),\ x_2(t),\ ...,\ x_n(t)>$ - are the variable states characterizing the state of the managed system at time t;

$Y_{<r>}(t)=<y_1(t),\ y_2(t),\ ...,\ yt>$ - Output variables, feedback outputs or environmental impact of the control system at time t;

$H_{<l>}(t)=<h_1(t),\ h_2(t),\ ...,\ h_l(t)>$ - observed variables are those state variables and output variables, which are observed by the control system at time t.

Output variables are generally associated with functional state variables

$$Y\langle r\rangle(t)=\psi\langle r\rangle\big(X\langle n\rangle(t)\big) \qquad (1)$$

,

where $\psi<r>$ is a vector-function symbol.

Variables are often called parameters. Arguments for all variables in the schematic are omitted for brevity.

III. Mathematical model

Enhancement of DCEM reliability indicator is carried out through the time indicator of reliability (durability) - the residual resource of brushes in a brush. In this case, the residual life of electric brushes should be determined when reaching the limit (minimum) value (height) h_{lim}. Under Δh_i we understand the real, found as a result of operation, value of brush wear.

The analysis of the data in Table 1 shows that the average wear rate of the electric brush is the most important operational indicator that characterizes its reliability. The values of Δh_i in Table 1 show that the values of residual life of the electric brush has a rather large scatter from the

mathematical expectation. In this regard, the brush failure occurs when

$$h_t \le h_{lim}, \qquad (2)$$

whereh_t is the height of the brush that has worked for time t, mm;

h_{lim} - the limit height of the electric brush, 45 mm.

The operating time of a brush up to the limit state as an element of the system with gradual failures (time of no-failure operation) - its resource

$$t_p = \frac{h - hlim}{v_{щ}} = \frac{H_0 - h_{[ad]}}{V_H} = \frac{\Delta h_{[ad]}}{V_H}, \qquad (3)$$

where$h$ – electric brush height, mm;

V_w – the intensity (rate) of its wear.

The values of the average wear rate of the electric brush, obtained in the process of observation, are defined as

$$\bar{v}_b = \frac{1}{n}\cdot\sum_{i=1}^{n} v_{bi}\ , \qquad (4)$$

Where $\bar{v}_b$ - average wear rate of electric brushes;

n - sample volume of brushes for testing;

v_{bi} - wear rate of i-brush;

The standard deviation of this speed will be

$$\bar{\sigma}_V = \sqrt{\frac{1}{n-1}\cdot\sum_{i=1}^{n}\left(v_{bi} - \bar{v}_b\right)^2} \qquad (5)$$

By setting different values of t_i and intervals of incremental wear of electric brushes Δh_i, we can determine the indices of sampling characteristics. By dividing into intervals of brush wear height Δh_i, we can find the number of values falling in the given interval to the limit of brush wear

By systematizing and processing experimental data taken from 85 units of urban rolling stock (streetcars KTM-5M (№71608) and trolleybuses Trolza-7 (№2341)), we can calculate the main quantitative indicators of reliability of BCA operation: probability of no-failure operation $P(t)$, probability of failure $Q(t)=1-P(t)$, frequency $\alpha(t)$ and intensity of failures $\lambda(t)$, average operating time before failure T_{av}, and resource - total operating time of the object before reaching the limit state of electric brushes [14].

In order to be able to predict the residual life (wear) of the brushes, it is necessary to determine the wear rate of the brushes and on this basis to suggest such a height (resource) of the brush that it is completely exhausted before reaching the time of technical repair (TR) or maintenance, where there is an opportunity to replace worn brushes with new ones [15].

In the experiment it is taken $\tau(t)$ - the remaining lifetime of the node, provided that it has not failed until time t - time of failure of the i-th brush. In other words, it is a numerical expression of the result of a random event (brush chipping, lateral wear and tear) [16]. After working for a certain time t, a random brush is selected from the total number of brushes in the experiment. The wear of the brush length is measured and the remaining life is determined. Thus, the measurement of one motor brush can be used to determine the need for replacing the entire set of brushes on the motor (up to 12 brushes on a trolleybus and up to 18 brushes on a railroad motor).

The maximum operating time of a brush before it reaches the limit state which is a failure. Brush failures can be divided into three types: mechanical, technological and operational failures. The percentage of failures of the third type is determined in the basic level at a particular enterprise, determining the volume of sampling data on the state of the brush during testing. The probability that after time t a node will operate faultlessly for a period of time$\tau(t)$ while

$$n(t)\leq N. \qquad (6)$$

where N is the number of tests of electric motor brushes;

n – the permissible number of brush failures that do not lead to a motor stop (determined by tests) in time t.

If the allowable number of failures of brushes in a set is n, then the probability of the event that at N tests no more than n failures will occur. Decision making is based on the sequential likelihood ratio criterion (probability ratio).

The probability of no-failure operation for time t means the probability of the event $\{\tau>t\}$, which consists in the fact that for time t the BCA does not fail, i.e. symbolically it is written as follows:

$$p(t)=P\{\tau>t\}, \qquad (7)$$

wheret is the set operating time;

τ - operating time of a brush to failure - a random variable[17].

If the brush-collector assembly under consideration can be in operable or in inoperable state, then for any moment of time t the following identity takes place:

$$p(t)+F(t)=1, \qquad (8)$$

where $F(t)=P\{\tau\leq t\}$ is the distribution function of the operating time τ to failure (the probability that the BCA will fail in time t)[19].

The operating principle and algorithm of the developed complex mathematical model can be shown with the help of the algorithm shown in Figure 3.

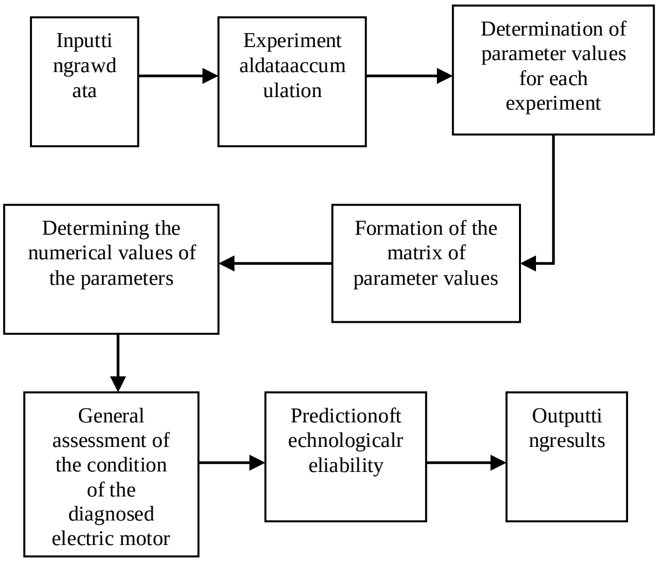

Fig. 3. – Algorithm for analyzing experiments to identify defects

IV. RESULTS AND DISCUSSION

On the other hand, in practice, when developing specific technical (vibration diagnostics) systems, it is impossible to meet all general requirements, without using human factor, including the definition of the automated system concept.

Vibration is often used as a diagnostic parameter. The vibration acceleration sensor is connected either to the brush holder, or a laser one is used. Sometimes vibration is determined by the deformation of the brush. Almost all malfunctions of the control panel affect the performance of the electric motor (Table 1. and Fig. 4).

TABLE I. THE FREQUENCIES COMPONENTS OF THE SPECTRUM OF VIBRATION, AS DIAGNOSTIC SIGNS OF THE PRESENCE OF DEFECTS OF A DIRECT CURRENT ELECTRIC MOTOR

Defect name	**Growth of vibration harmonics**	**Note**
Static clearance eccentricity, skewed poles	$f_{zп}$, f_{zv} R or T	Vibration increase with load change
Defects in the armature windings, breakage of the collector plate	$2pf_п$ $kf_{zп}\pm k_1 f_п$ $kf_{zv}\pm 2pf_п$ R or T	-
Switching defects	$k\ f_{zv}$ R or T	Growth with load change
Wear of brushes, collector damage	$k_1\ f_{zv}\pm k_2 f_п$ R or T	-
Supply voltage ripple	kf_1 R or T	-

The duration of the tests T_n must be at least $0.2\bullet T_p$ and the probability of providing a resource is determined by the formula,

$$P(Tp)=\gamma/100 \qquad (9)$$

whereT_p is the expected operating time (resource) up to the limit state;

γ is the number of products that do not reach the limit state with a given probability. It is taken equal to 90, 95, 99 and 99.5%.

For diagnostics, the received signal is converted from an analog to a digital form[20]. Then, a spectral analysis of the signal of the vibration spectrum, which is obtained during the measurements, is made and is divided by the frequencies of the computer(fig. 4) [18].

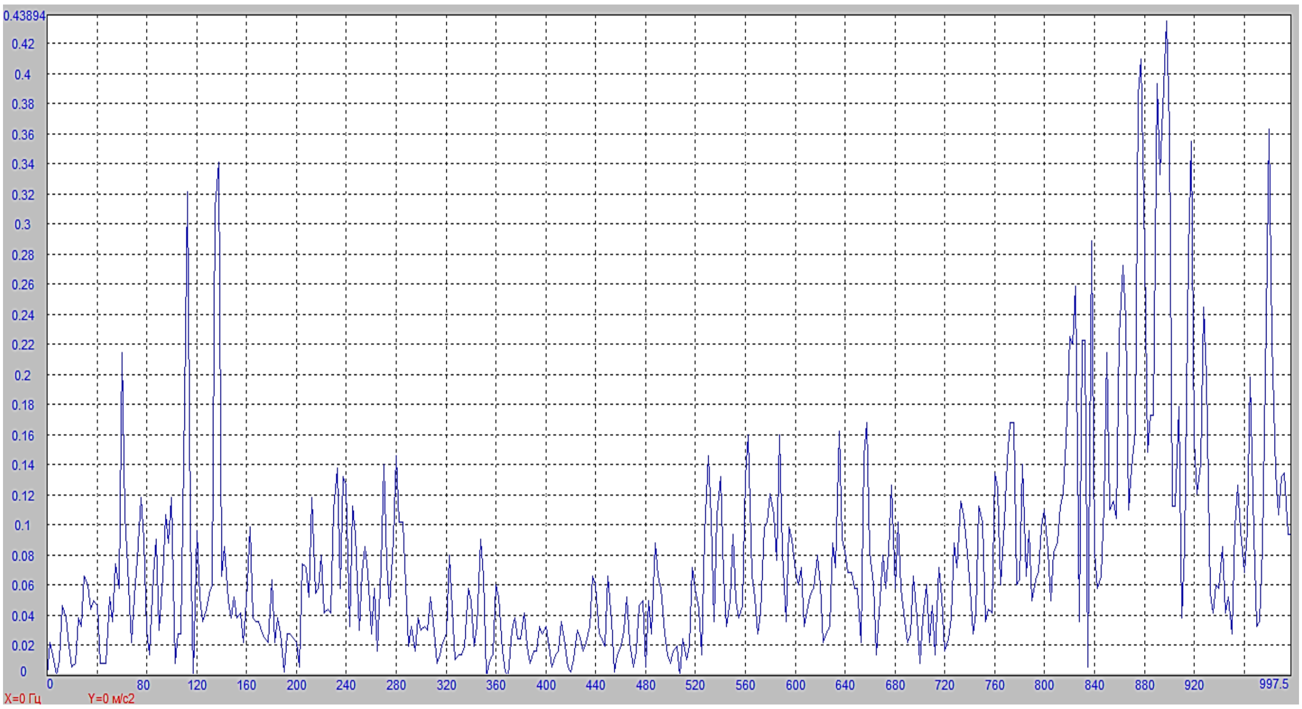

Fig 4. Vibration spectrum range by brush wear in the software package

The classification of information by structure is given in Table. 2.

TABLE II. CLASSIFICATION OF INFORMATION BY STRUCTURE

Typeofinformation	Symbol	Structurecharacteristic
natural	{f},{t},{n}	Initialinformationstructure
Normalized	M, D, L, {x}, {f} {n}	Reduced to a single scale M, range D and origin L
Complexed	{y, t, h}	Reduced to a complex with generalized coordinates y, t, h
decomposed	$\{x,t,n\} \to xt \to x$ $\to xn \to t$ $\to tn \to n$	Number of dimensions, structure and layout converted
Generalized	G_A {x, t, n}	Eliminated redundancy, allocated a significant part of the condition A
Discrete (quantized)	$\{x^*\},\{t^*\},\{n^*\}$	Selected counts at discrete times
Dimensionless	$\{q_x\}, \{q_t\},\{q_n\}$	Discrete counts are reduced to dimensionless form
coded	—	Information is presented in a numerical code or in some other alphabet

Natural information reflects the real existence of objects. It has an analog form, is clogged with noise, and is not optimal in terms of ranges and reference points of parameter values. All these features are due to the physical properties of the reflected object or phenomenon. Natural information can be represented as a set of values {x}, points in time {t} and points in space {n}.

Normalized information differs from natural information in that each set {x}, {t}, {n} in it has already been reduced to the same scale, range, origin and other common unified characteristics. Normalized information can be interpreted as a result of the impact on natural information of operators: scale M, range D and localized L.

In all cases, the running DC electric motor shall be monitored and spectrally analysed. If it is possible to continuously monitor the parameters (vibration and wear of the brush) of the technical condition of the BCA with the help of the proposed set, simplified methods can be used, in which forecasting is carried out according to one parameter of technical condition:

- forBCAoperating under static load and general uniform load, calculation shall be made to reduce the height of the brush;

- for the DCEM, for which there is sufficient information on functional parameters to extrapolate values to subsequent service life, the calculation is made to change these parameters to limit values.

V. CONCLUSION

It was determined that the primary failures of the switchgear and controlgear assemblies include brush wear and tear.To determine the brush reliability and residual life of brushes a complex mathematical model of statistical data processing is developed that enables to classify the failures types and enables, unlike the existing models, to determine the refined brush life on the basis of brush wear limit height. To calculate brush reliability it is necessary and sufficient to know values of average speed V_h and brush wear height Δh_i in short-term (for urban electric transport) and long-term (for railway locomotives) operating modes of DCEM. In order to construct some function for automatic calculation of technical condition estimations, it is necessary to determine those product properties that, in total, are sufficient, in terms of operation, to obtain the required quantitative or qualitative estimates. In this case, since we are talking about quantitative estimates of technical condition, each property of the sufficient properties total set in turn, must be represented by some quantitative characteristic. It is then obvious that no direct measurement results can be directly interpreted as technical condition assessments. Properties cannot be directly measured. The properties of products can be estimated from the results of some kind of direct measurement. Therefore, for technical objects it seems appropriate to construct functions for automatic generation of quantitative estimates of technical condition in the form of some dependence on a priori specified specific structural parameters.

REFERENCES

[1] Olga Filina, Khalil Vakhitov, Artyom Starodubets, Olga Salnikova. "Vibration Diagnostics of the Brush-Collector Assembly, as Means of Assessing", 2022 4th International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE), 2022.

[2] O. A. Filina and A. N. Tsvetkov, "Evaluation of the operation all ifeof direct current motors," IOPConf. Series: Materials Science and Engineering, 2019.

[3] Olga A. Filina, Anna V. Yashagina, and Olga V. Salnikova, "Determination of the Characteristic Points of Approximation for Traction Electric Machines of Electric Rolling Stock", 2021 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), 2021.

[4] O. A. Filina andO. V. Salnikova, "Topical Problems of Mechanical Engineering,"2020IOPConf. Series:MaterialsScienceandEngineering, 2020.

[5] R. G. Mannapov. "Predicting the reliability of equipment by statistical analysis of operationalparameters", Chemical and Petroleum Engineering, 1990.

[6] Yu.S.Sergeev, V.M.Sandalov, and G.E.Karpov, "DevelopingModelofSwitchedReluctanceElectricVibrationDrivefor DebuggingofExecutiveBodyComplicatedMovementsControlAlgorithms" 2018 Int. Conf. on Industrial Engineering, Applicationsand Manufacturing, 2018.

[7] YangYu, LeyaoCong, XiaTian, ZengqiangMi, YangLi, ZhenFan, and HuiFan,"Astatorcurrentvectororientationbasedmulti-objectiveintegrativesuppressionsofflexibleloadvibrationandtorqueripple forPMSMconsideringelectricalloss,"CESTransactionsonElectrical MachinesandSystems,2020.

[8] RyoheiMatsuura, TaketoSugiyama, TakaharuTakeshita, Yugo Tadano, Shizunori Hamada, and HajimeKubo,"CurrentcontrolofIPMSMtoavoidvoltagesaturationforchangingfrequencyandamplitudeofvibrationtorquereference,"2017IEEE12thInt.Conf.onPowerElectronicsandDriveSystems, 2017.

[9] MuhammadSarfrazMoiz, ShazaibShamim, MuhammadAbdullah, HamdanKhan, ImtiazHussain, AnasBinIftikhar, and T.D.Memon,"HealthMonitoringofThree-PhaseInductionMotorUsingCurrentandVibrationSignatureAnalysis," 2019Int.Conf.onRoboticsandAutomationinIndustry, 2019.

[10] XiaohuaLi, XiaotongTian, YuefeiWang, RongjianZhao, and WendanHe,"AnalysisofVibrationandNoiseofIPMSMforElectricVehiclesunderInverterHarmonicinaWide-speedRange,"201922ndInt.Conf.onElectricalMachinesandSystems, 2019.

[11] SahilMishra, AlanB.Palazzolo, XuHan, YashuLi, and ChrisKulhanek,"TorsionalVibrationsinOpenLoopVoltsHertzVariable FrequencyDriveInductionMotorDrivenMechanicalSystems,"2020IEEETexasPowerandEnergyConf., 2020.

[12] H.Yu, Z.Wang, H.Chuang, and C.Lin,"Designandmodel-freepredictivecurrentcontrolfordualair-gaptransverse-fluxsensorlesspermanentmagnetbrushlessdirectcurrentmotorswithlowrareearthmaterial,"2015IEEEInt.MagneticsConf., 2015.

[13] V V Kharlamov, D I Popov, M F Baysadykov. "Determination wear intensity of electrical brushes in DC machines considering impact of collector's surface", Journal of Physics: Conference Series, 2019

[14] T. A. Aliev, L. N. Kartvelishvili. "Principles of evaluating the ecological reliability of irrigation systems", Hydrotechnical Construction, 1993

[15] Nicola Montinaro, Donatella Cerniglia, Giuseppe Pitarresi. "Defect detection in additively manufactured titanium prosthesis by flying laser scanning thermography", Procedia Structural Integrity, 2018

[16] Arkadov, "Terminology, concepts and definitions", Probabilistic safety assessment for optimum nuclear power plant life management (PLiM), 2012.

[17] E M Khusnutdinova, P P Pavlov, V P Fandeyev, R N Khizbullin, A N Khusnutdinov, I V Cherepen'kin. "Comprehensive Test Procedure for Digital Instruments and Devices of Automated Versatile Systems", IOP Conference Series: Materials Science and Engineering, 2020

[18] Kai Michels. "Fundamentals of Control Theory", Studies in Fuzziness and Soft Computing, 2006.

[19] J. Franco, M. Rider and R. Romero, "A Mixed-Integer Linear Programming Model for the Electric Vehicle Charging Coordination Problem in Unbalanced Electrical Distribution Systems", IEEE Transactions on Smart Grid, vol. 6, no. 5, pp. 2200-2210, 2015.

[20] A.N. Khusnutdinov, E.M. Khusnutdinova and V.M. Butakov, "Operation of brushes with increased service life on traction machines of electric vehicles", IOP Conference Series: Materials Science and Engineering,vol.570, №012053,2019.